Does a Fiber Reinforced Thermoplastic Door Structure Meet the Energy Absorption Requirements for a Side Impact Crash Test?

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University of Delaware Shridhar Yarlagadda, Lukas Fuessel, Bazle Z. Haque

Honda R&D Americas, Inc Skye Malcolm, Duane Detwiler
1. Motivation
2. Grand challenge
3. Project overview
4. Design development & material overview
5. Mechanical performance
6. Future work
Motivation

- CAFE 2025 – Fuel economy targets
- CO₂ Emissions 2007/46/EC – CO2 emissions targets
- End-of-life vehicle directive 2000/53/EC – 95% reuse and recovery from 1st January 2015
- “Highest mass contribution is from the load bearing structure” (15% to 30%)
Fuel Economy Regulation vs Market Trend

Avg MPG and Targets vs Model Year

- CAFE targets
- MPG (EPA Unadjusted Laboratory)

Increases in hybridizations
Gap in fuel economy regulation, requirement for light weighting

Technology Portfolio for Efficiency

- **Efficiency gains – Miles/Grams of CO₂**
  - **High**
  - **Low**

- **Cost of Vehicle $**
  - **High**
  - **Low**

- **Lightweighting Technologies**
  - Diesel
  - Better Aerodynamics
  - Low Rolling Resistance Tires

- **Powertrain Technologies**
  - Aluminum BiW
  - Turbo Charging
  - CNG
  - Engine Downsizing

- **General & Miscellaneous**
  - CFRP BiW
  - HCCI
  - Plug-in Hybrid
  - Hydrogen
  - Full Electric
  - Larger Bolt-on Composite parts
  - Ultra Lightweight Closures Systems

- **Ultra Lightweight Closures**

- **Systems**?
1. **Achieve a 42.5% weight reduction (addresses goals in the DOE-VT MYPP)**
   - Base weight = 31.8 kg
   - Target Weight = 18.28 kg

2. **Zero compromise on performance targets**
   - Similar crash performance
   - Similar durability and everyday use/misuse performance
   - Similar NVH performance

3. **Maximum cost induced is 5$ per pound. (.453 kg)**
   - Allowable cost increase = \([31.8 - 18.28]/.453\)*5 = $150.1 per door

4. **Scalability**
   - Annual production of 20,000 vehicles

5. **Recyclability**
   - European standards require at least 95% recyclability
   - Project goal is 100% recyclable (self imposed)
Fine Prints of the Grand Challenge

- Weight and cost target is for entire door assembly.
  - Not all components in the door assembly have equal lightweight potential
    - This drives a more aggressive target for the door frame.

"Material substitution is not a solution"
Understating requirement at system level and decomposing targets and definition to lower systems.
Project Constraints

Constraint set forth by DOE
• Need to use commercial available material systems
• The prototype door has to meet all attributes of the baseline door
• Technology for scalability has to ready available

Constraint set forth by Honda
• Should use same sealing geometry
• Should have all the equipment as the baseline door
• Should have un-noticeable difference in Class A finish
• Should meet all durability and aging requirements from Honda

Constraint set forth by the team (internal)
• Should be 100% recyclable/reprocessable
Benchmarks for lightweight door concepts and understanding performance vs cost tradeoffs.

- **Steel Door Frame** - E.g. Honda MDX
- **Aluminum Door Frame** - E.g. Audi A8
- **Magnesium Door Frame** - E.g. Porsche Panamera

**DOE Cost Target**

- **Carbon Fiber Reinforced Thermoplastic Door Frame** - E.g. BMW i8

**Carbon Fiber Reinforced Thermoset Door Frame**
Project Timeline

Year 1
- Target definition

Year 2
- Concept development and simulation loops
  - Concept Development
  - Virtual modeling and simulation
  - Tooling development
  - Manufacturing simulation
  - Manufacturing affected material property generation

Year 3
- Targets not achieved

Year 4
- Plant simulation
  - Virtual Plant simulation for scalability and cost validation

Prototype manufacturing
- Tooling manufacturing
- Prototype manufacturing

Testing and validation
- Static performance
- Door level crash test
- Vehicle level crash test

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Material Data Generation

- Material selection
- Manufacturing process selection
- Material card generation
Baseline Benchmarking

**Mass distribution in the baseline door**

- **Rigid polymer**: 21%
- **Glass**: 13%
- **Elastomer**: 4%
- **Metal**: 62%

**Frame 60% Reduction**
Current weight: 15.45 kg
Target weight: 6.18 kg

**Window 20% Reduction**
Current weight: 3.70 kg
Target weight: 2.77 kg

**Electronic 0% Reduction**
Current weight: 3.0 kg
Target weight: 3.0 kg

**Trim 30% Reduction**
Or elimination
Current weight: 3.24 kg
Target weight: 2.26 kg
Material Data Generation

Why thermoplastic reinforced carbon fiber?

- +60% light-weighting target structural members
- +80,000 doors annually
- 100% recyclable

<table>
<thead>
<tr>
<th></th>
<th>Steel</th>
<th>Aluminum</th>
<th>Thermoset Composites</th>
<th>Thermoplastic Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Weight Potential</td>
<td>Medium</td>
<td>High</td>
<td>Very High</td>
<td>Very High</td>
</tr>
<tr>
<td>Material Cost</td>
<td>Moderate</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Reprocessing/Recyclability</td>
<td>Good</td>
<td>Good</td>
<td>Not</td>
<td>Good</td>
</tr>
<tr>
<td>Part Manufacturing</td>
<td>Very Fast</td>
<td>Very Fast</td>
<td>Slow</td>
<td>Fast</td>
</tr>
<tr>
<td>Joining Speed</td>
<td>Fast</td>
<td>Moderate</td>
<td>Very Slow</td>
<td>Very Slow</td>
</tr>
<tr>
<td>Average Takt Time Per Vehicle</td>
<td>55-100 sec</td>
<td>120-200 sec</td>
<td>480 sec</td>
<td>Tbd</td>
</tr>
</tbody>
</table>

Material data generation

- Material scouting
- Sample manufacturing at similar conditions similar to mass production
- Standardized testing
- Archiving raw material data
- Translating into appropriate material cards for FEA

- Why thermoplastic reinforced carbon fiber?
  - +60% light-weighting target structural members
  - +80,000 doors annually
  - 100% recyclable

Light Weight Potential: Steel (Medium), Aluminum (High), Thermoset Composites (Very High), Thermoplastic Composites (Very High)
Material Cost: Steel (Moderate), Aluminum (Medium), Thermoset Composites (High), Thermoplastic Composites (High)
Reprocessing/Recyclability: Steel (Good), Aluminum (Good), Thermoset Composites (Not), Thermoplastic Composites (Good)
Part Manufacturing: Steel (Very Fast), Aluminum (Very Fast), Thermoset Composites (Slow), Thermoplastic Composites (Fast)
Joining Speed: Steel (Fast), Aluminum (Moderate), Thermoset Composites (Very Slow), Thermoplastic Composites (Very Slow)
Average Takt Time Per Vehicle: Steel (55-100 sec), Aluminum (120-200 sec), Thermoset Composites (480 sec), Thermoplastic Composites (Tbd)
Material Systems Overview

**Strength/Stiffness and Cost**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScF Foamed Polymer</td>
<td>Micro cells (Gas Bubbles)</td>
</tr>
<tr>
<td>Pure Polymer</td>
<td></td>
</tr>
<tr>
<td>Short Fiber Reinforced Polymer</td>
<td>Fiber lengths up to ~5 mm</td>
</tr>
<tr>
<td>Woven Fiber Reinforced Polymer</td>
<td>Woven fiber</td>
</tr>
<tr>
<td>Endless Fiber Reinforced Polymer</td>
<td>Continuous fiber</td>
</tr>
</tbody>
</table>

**Suppliers and partners for materials**

- Advanced Composites
- Asahi Kasei
- LanXess
- Barrday
- Cytec
- Tencate
Material Data Generation

**Coupon Manufacturing**

- **Material Sourcing**
  - Off the shelf materials were compared and most promising candidates were sources.

- **Material Processing**
  - Off the shelf materials were compared and most promising candidates were sourced.

- **Sample Screening and Preparation**
  - 0 and 90 Samples were cut using a diamond coated blade.
  - Scanned for voids using a CT scanner. Tabbed using epoxy-based adhesives.

- **Bonding Strain Gauges**
  - Strain gauges were used in order to record true strain.

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**Material testing**

- **ASTM D 039**
  - Samples tested in 0° and 90° orientations
  - At least 5 samples were tested
  - Crosshead speed of 2.5 mm/min

- **ASTM D6641**
  - Samples tested in 0° and 90° orientations
  - At least 5 samples were tested
  - Crosshead speed of 1.3 mm/min

- **ASTM D3410**
  - Samples tested in 45° orientations
  - At least 5 samples were tested
  - Crosshead speed of 1.5 mm/min
Material Cards Selection

MAT 54

| MAT 54 | 1.462 | 59 | 59 | 0.05 |

MAT 59

| MAT 59 | 5.59 | 59 | 59 | 0.05 |

MAT 054

| MAT 054 | 1.0 | 1.0 | 1.05 | 0.15 | 1000 | 1000 |

MAT 059

| MAT 059 | 1.0 | 1.0 | 1.0 | 0.15 | 1000 | 1000 |

MAT 054:
- Even though MAT 059 is non-linear, the parameters controlling the non-linearity is fixed and users have no control on those. With a conservative approach, MAT 054 is linear-elastic till maximum stress yield.
- The MAT 8 material model was used for the static load cases. It defines the material properties for linear temperature-independent orthotropic material for two-dimensional elements.

Both these models have been validated by our collaborators at University of Delaware in the B-Pillar project funded by NHTSA and BMW.

1. Composite B Pillar
2. Deformation @ high velocity crash loading
3. Experimental vs Simulation
Material Testing: Endless Fiber Reinforced Polymer

Tension 0 and 90

In-plane shear behavior was characterized using the tension and compression tests on a [±45º] laminate.

Compression 0 and 90

• In-plane shear behavior was characterized using the tension and compression tests on a [±45º] laminate.

• Tension mode allowed fiber rotation due to the thermoplastic matrix toughness and axial strain was measured using optical methods with markers and high-resolution video cameras.

• Compression mode was performed using the shear-loaded compression method (IITRI) and strains measured to the limit of strain gages.
Compression mode was performed using the shear-loaded compression method (IITRI) and strains measured to the limit of strain gages.

Load-displacement response was used to identify plateau stress and displacement limits.
Concept Development

- Concept development
- Sub-components detailing
- Multi-material strategy
Year 1&2: Concept Development Summary

Phase 1
2016

- Hand drawn sketches.
- High level material selection.

Phase 2
2016

- Rough CAD models using generic door geometries.
- Initial FEA simulations for simple static load cases.

Phase 3
2016

- Design workshop was conducted at CUICAR.
- The team developed and hand-sketched 7 concepts for door frame.

Phase 4 & 5
2017

- Detailed CAD models were generated.
- FEA simulations were performed to validate static performance in compliance with Honda’s targets.
- Down selection to one concept.

Phase 6
2018

Final Design (C2)

- FMVSS 214 static test performance was used as metric for concept down selection.
Key changes

- New outer beltline stiffener
- New lower door stiffener
- Sash reinforcement integrated into the inner beltline stiffener for part consolidation.

Design version 7 - 2018

Design version 11 - 2019
Concept Details: Inner Panel

Structural components of inner panel

1. Inner frame
   • Thermoformed inner panel with integrated trim.
   • Material: Woven fabric with UD reinforcements.

2. Anti intrusion beam
   • Hot stamped and welded
   • Material: Ultra high strength steel

3. Inner beltline stiffener
   • Thermoformed shell with mounting interfaces for the inner components.
   • Material: Woven fabric with UD reinforcements.

4. Outer beltline stiffener
   • Extruded aluminum beams with a stamped handle mount.
   • Material: Aluminum 6061

5. Lower Reinforcement (New Part)
   • Stamping
   • Material: Aluminum 6061
Design Overview

Design philosophy

- Maximize functional integration
- Minimize part count
- Eliminate lazy material by optimization
- Simplify assembly

42.5% Lightweighting $950 Cost target

Design highlights

- One piece structural frame
- Removable class A panel
- No trim panel
All door subsystems can be divided into 4 major categories

1. Interior trim
2. Inner frame
3. Door internals
4. Class A panel
Concept Details: Class A Panel

- Added reinforcement to the injection molded outer panel for preventing oil-canining, and improving stiffness for aerodynamic loads
- Reduced wall thickness from 2.2 mm to 1.2mm
- Almost no impact on weight

<table>
<thead>
<tr>
<th>Outer Side</th>
<th>Inner Side</th>
</tr>
</thead>
</table>

![Outer Side](image1)

![Inner Side](image2)
To minimize weight and cost, this concept has no interior panel. Instead it has a few injection molded parts to meet functional requirements.

Non-structural trim components

1. Upper padding
   • Leather laminated with foam.
2. Middle padding
   • Leather laminated with foam.
3. Hand rest
   • Natural wood, back molded with ABS
4. Map pocket
   • Injection molded carbon fiber SFT or ABS

These parts approximately weigh 1.34 kg in contrast to 3.49 kg in baseline door. Further weight reduction of 0.25Kg is expected with optimization.
Finite Element Strategy

• Load requirements breakdown
• Concept design performance : Static performance
• Concept design performance : Dynamic performance
Phase I FEA Optimization: Static Load Cases

a. Door sag (DS)
b. Door sash (A and B)
c. Door over opening
d. Beltline stiffness
e. Mirror mount rigidity
f. Speaker mount stiffness
g. Door handle pull rigidity
h. Map pocket pull rigidity
i. Window regulator (figure not displayed here)
Modelling Endless Fiber & Woven Materials

- These are materials are anisotropic by design
- FEA Material model inputs known based on our MAT 54 card
- Good knowledge base for FEA simulation exists with our collaborators at Clemson University and University of Delaware

<table>
<thead>
<tr>
<th>PLY</th>
<th>Laminate Design</th>
<th>Layup Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>90°</td>
<td></td>
</tr>
</tbody>
</table>

- Manufacturability
- Performance requirement
- Commercial availability

- Performance driven
- Can use FEA optimization to determine laminates

- Performance driven
- Manufacturability
- Can use FEA optimization to determine laminates
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Static Performance (Daily Use and Misuse)

- These linear load cases represent door performance for daily use and occasional misuse of the door.
- These targets are used for optimizing the composite ply configurations.

<table>
<thead>
<tr>
<th>Targets</th>
<th>Baseline Door</th>
<th>Composite Door (V11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural frame mass</td>
<td>&lt; 7.26 Kg</td>
<td>15.1 Kg</td>
</tr>
<tr>
<td>Door Sag - Fully open</td>
<td>&lt; 5 mm</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Sash Rigidity at point A</td>
<td>&lt; 3.5 mm</td>
<td>0.93 mm</td>
</tr>
<tr>
<td>Sash Rigidity at point B</td>
<td>&lt; 4 mm</td>
<td>0.91 mm</td>
</tr>
<tr>
<td>Beltline stiffness-Inner panel</td>
<td>&lt; 1.5 mm</td>
<td>1.34 mm</td>
</tr>
<tr>
<td>Window regulator (Normal)</td>
<td>&lt; 1 mm</td>
<td>6.88 mm</td>
</tr>
<tr>
<td>Mirror Mount rigidity in X</td>
<td>&lt; 0.92 mm</td>
<td>0.57 mm</td>
</tr>
<tr>
<td>Mirror Mount rigidity in Y</td>
<td>&lt; 2.25 mm</td>
<td>0.86 mm</td>
</tr>
<tr>
<td>Door Over opening</td>
<td>&lt; Baseline mm</td>
<td>24.7 mm</td>
</tr>
<tr>
<td>Speaker mount stiffness</td>
<td>&lt; Baseline mm</td>
<td>0.35 mm</td>
</tr>
</tbody>
</table>
Dynamic load cases

1. FMVSS 214s (static)
   A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

2. FMVSS 214 (DB)
   A moving deformable barrier is impacted with a stationary vehicle at 55 km/h.

1. FMVSS 214 (RP)
   The vehicle is rammed into a rigid pole at 32 km/h at 75 deg.
FMVSS 214: Quasi Static Pole Test

- Has higher force response than baseline steel door.
- Significant crush resistance is offered even after the inner panel fails.
IIHS Side Impact Protocol (MDB)

- The moving deformable barrier (MDB) impacts the car perpendicularly. Such configuration together with the barrier bumper height makes this test more challenging than FMVSS 214
- The impact speed is 50 km/h and the impact mass is 1500 kg
- The composite door outperforms the baseline steel door

**Baseline steel door**

**Composite door**
Gauging Metrics for IIHS SI- MDB

- **Success** *(Green)*
  - Below baseline target values (<b)

- **Tolerable** *(Yellow)*
  - More than baseline values but smaller than 10% difference (>b, <b+10%)

- **Failure** *(Red)*
  - More than 10% above baseline value (>b+10%)

- **No exposed crack in the door interior.**

<table>
<thead>
<tr>
<th>Key Performance Indicator</th>
<th>Baseline [mm]</th>
<th>Composite [mm]</th>
<th>Difference [mm]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupant survival space</td>
<td>134.3</td>
<td>140</td>
<td>5.7</td>
<td>4.2%</td>
</tr>
<tr>
<td>Maximum intrusion at roof</td>
<td>62.1</td>
<td>48.16</td>
<td>-13.94</td>
<td>-22.45%</td>
</tr>
<tr>
<td>Maximum intrusion at window sill intrusion</td>
<td>279</td>
<td>233</td>
<td>-46</td>
<td>-16.5%</td>
</tr>
<tr>
<td>Intrusion at hip location of the dummy</td>
<td>175.6</td>
<td>125.64</td>
<td>-49.36</td>
<td>-28.1%</td>
</tr>
<tr>
<td>Maximum intrusion at lower door region</td>
<td>210.4</td>
<td>205.76</td>
<td>-4.64</td>
<td>-2.2%</td>
</tr>
</tbody>
</table>

*Baseline steel door

Composite door*
FMVSS 214 Rigid Pole

- In this crash mode, the vehicle is mounted on a mobile platform and is impacted with a rigid pole at 75° to the length of the vehicle.
- For this test, a hybrid III 5th percentile female crash dummy was used for positioning the vehicle since it is the most challenging crash mode for the rigid pole test.
- The composite door had adequate performance in this test.
Gauging Metrics for FMVSS 214 Rigid Pole

- **Success (Green)**
  - Below baseline target values (<b)
- **Tolerable (Yellow)**
  - More than baseline values but smaller than 10% difference (>b, <b+10%)
- **Failure (Red)**
  - More than 10% above baseline value (>b+10%)
- No exposed crack in the door interior.

<table>
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<tr>
<th>Key Performance Indicator</th>
<th>Baseline [mm]</th>
<th>Composite [mm]</th>
<th>Difference [mm]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum intrusion at B-pillar</td>
<td>150.9</td>
<td>164</td>
<td>13.1</td>
<td>8.68%</td>
</tr>
<tr>
<td>Maximum intrusion at sill intrusion</td>
<td>293.4</td>
<td>287.6</td>
<td>-5.8</td>
<td>-1.98%</td>
</tr>
<tr>
<td>Maximum intrusion at roof</td>
<td>254</td>
<td>259.8</td>
<td>5.8</td>
<td>2.28%</td>
</tr>
<tr>
<td>Maximum intrusion at window sill intrusion</td>
<td>434.5</td>
<td>438.1</td>
<td>3.6</td>
<td>0.83%</td>
</tr>
<tr>
<td>Intrusion at Hip location of the dummy</td>
<td>355.3</td>
<td>336.5</td>
<td>-18.8</td>
<td>-5.29%</td>
</tr>
<tr>
<td>Maximum intrusion at lower door region</td>
<td>440.3</td>
<td>443.1</td>
<td>2.8</td>
<td>0.64%</td>
</tr>
</tbody>
</table>

Baseline steel door

Composite door

This presentation does not contain any proprietary, confidential, or otherwise restricted information
• Material Card Development
  • Material testing and card development loops were carried out for endless and woven carbon fiber reinforced PA 66 composites were successfully carried out.
  • MAT 8 and MAT 54 cards were developed for Static and Dynamic load cases.

• Design Development
  • A multi-material strategy that leverages the stiffness of endless and woven composites with the plasticity of steel was developed. Where a steel anti-intrusion beam was lighter and cost effective than a composite alternate.

• Static and Dynamic Load Requirements
  • Proposed design was able to meet static load and dynamic load targets (FMVSS 214 s, 214 (DB), 214 (RP) ) in line with NHTSA and OEM Partners targets.
## Collaborations

<table>
<thead>
<tr>
<th>Key Organizations</th>
<th>Role</th>
<th>Responsibilities</th>
</tr>
</thead>
</table>
| **Clemson University** | Principal investigator | • Project management  
  • Design development  
  • Discontinuous fiber material characterization  
  • Tooling design & simulation  
  • Manufacturing  
  • Linear, Non-linear & NVH analysis  
  • Cost modeling & factory layout |
| **University of Delaware** | Co - PI | • Non-Linear analysis  
  • Continuous fiber material characterization |
| **Honda** | OEM Partner | • Target definitions  
  • Student mentoring  
  • Computation support for running complex simulations  
  • Component & vehicle crash testing |
| **Corning** | Supplier | • Lightweight glazing design & prototyping |

**Suppliers, software and general participants**

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### Core Participant Profiles

<table>
<thead>
<tr>
<th>Institution</th>
<th>Advisor</th>
<th>Personal</th>
<th>Standing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clemson University</td>
<td>Srikanth Pilla (PI)</td>
<td>Veera Aditya Yerra</td>
<td>PhD students</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sai Aditya Pradeep</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gang Li (Co-PI)</td>
<td>Anmol Kothari</td>
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<td></td>
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<td>Madhura Limaye</td>
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<td></td>
<td></td>
<td>Gaurav Dalal</td>
<td>Master’s Student</td>
</tr>
<tr>
<td></td>
<td>Srikanth Pilla</td>
<td>Senthil Ramesh</td>
<td>Master’s Student</td>
</tr>
<tr>
<td>University of Delaware</td>
<td>Shridhar Yarlagadda (Co-PI)</td>
<td>Bazle Haque</td>
<td>Research Faculty</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lukas Fuessel</td>
<td>Visiting scholar</td>
</tr>
<tr>
<td></td>
<td>OEM Partner</td>
<td>Skye Malcolm</td>
<td>Principal Engineer</td>
</tr>
<tr>
<td></td>
<td>OEM Partner</td>
<td>Duane Detwiler</td>
<td>Chief Engineer</td>
</tr>
</tbody>
</table>

No. of students worked/working on this project: 7
Future Work

1. Manufacturing simulations and tooling
   Develop manufacturing simulations, tooling designs and collaborate with tooling and prototyping partners.
   1. Manufacturing simulations for thermoforming and injection molding.
   2. Thermoforming tooling and process design
   3. Injection molding tool design

2. Mass production plan and cost model refinement
   Developing mass production processes and implementing them in a virtual plant layout tool and determining the costs for the same.
   1. Virtual plant layouts for mass production.
   2. Developing costing models for estimation and optimization.

3. Prototype manufacturing
   Manufacturing functional prototypes with actual material systems.
   1. Prototype door frames with actual material system and manufacturing process similar to mass production.

4. Testing
   Subject the door to similar tests which were preformed on the baseline door.
   1. Mechanical testing for stiffness.
   2. Crash testing
   3. Fit and Finish
   4. Accelerated aging
Acknowledgment to

Vehicle technology office DE-EE0007293

Honda R&D Americas

Thank you.